

Initial Results from the Nobeyama Molecular Gas Observations of Distant Bright Galaxies

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Abstract

We present initial results from the CO survey toward high redshift galaxies using the Nobeyama 45m telescope. Using the new wide bandwidth spectrometer equipped with a two-beam SIS receiver, we have robust new detections of three high redshift ($z = 1.6 - 3.4$) submillimeter galaxies (SXDF 1100.001, SDP9, and SDP17), one tentative detection (SDSS J160705+533558), and one non-detection (COSMOS-AzTEC1). The galaxies observed during the commissioning phase are sources with known spectroscopic redshifts from previous optical or from wide-band submm spectroscopy. The derived molecular gas mass and line widths from Gaussian fits are $\sim 10^{11} M_{\odot}$ and $430 - 530 \text{ km s}^{-1}$, which are consistent with previous CO observations of distant submm galaxies and quasars. The spectrometer that allows a maximum of 32 GHz instantaneous bandwidth will provide new science capabilities at the Nobeyama 45m telescope, allowing us to determine redshifts of bright submm selected galaxies without any prior redshift information.

Key words: telescopes — galaxies:high-redshift — galaxies:starburst — cosmology:observations

1. Introduction

Single dish submm telescopes equipped with wide bandwidth bolometer cameras have discovered a large population of galaxies in the distant universe that are extremely bright in mm/submm wavelengths (submillimeter galaxies (SMGs); e.g. Smail et al. 1997; Hughes et al. 1998; Greve et al. 2008; Scott et al. 2010; Hatsukade et al. 2010). The bright ($\gtrsim 1 \text{ mJy}$) SMG population typically shows evidence of enhanced massive star formation activity (SFR $\gtrsim 500 M_{\odot} \text{ yr}^{-1}$) with rapid gas consumption timescales ($\sim 40 \text{ Myr}$; Greve et al. 2005) and complex kinematics (Tacconi et al. 2008), which are all consistent with the properties expected for gas-rich major mergers at high redshifts. Results from these early observations are also consistent with the scenario where present-day massive galaxies acquire the bulk of their stellar mass at early epochs.

SMGs contribute 10 - 20% to the cosmic star formation at $z \sim 2 - 3$ (Hatsukade et al. 2010), but the lack of

precise redshifts have been the significant source of uncertainty. The redshift determination has been further hampered by the faintness of the optical counterparts even for those that are identified through direct submm interferometric imaging (e.g.; Iono et al. 2006; Younger et al. 2007). Uncertainties in the redshifts also affect the derivation of the clustering strength (Hatsukade et al., in prep) and the dark halo mass, which are both important parameters in the framework of the cold dark matter (CDM) cosmology.

The most direct way to determine the redshifts of SMGs is to conduct wide-band spectroscopic observations in the radio/mm/submm wavelengths through detections of the carbon monoxide (CO) emission. Recent observations using single dish telescopes have shown this to be effective (i.e. GBT-Zpectrometer, IRAM 30m-EMIR, CSO-Zspec, LMT-RSR; Erickson et al. 2007; Weiss et al. 2009; Harris et al. 2010; Lupu et al. 2010; Carter et al. 2012). Significant detection of two consecutive CO rotational transitions is needed for a secure determination of the redshift. In addition, these observations will allow us

to quantify the molecular gas mass and its dynamical status through the CO line width. This will further allow us to derive the gas mass fraction, star formation efficiencies, and the gas-to-dust mass ratio, all of which are important quantities related to their physical conditions and possibly their future evolution.

The 45m telescope at Nobeyama has undergone a major upgrade, with an installation of a new two-beam receiver, an intermediate frequency (IF) transmission system, an Analogue-to-Digital Converter (ADC) with a sampling rate of 4 GHz, and a new 32 GHz wide spectrometer. The final goal of this project is to obtain redshifts of the bright submm sources blindly from CO observations that are near or beyond the peak of the cosmic star formation. In order to assess the capabilities of the newly upgraded 45m telescope, we have targeted five sources that are bright in submm continuum and have spectroscopic redshifts, determined either via conventional optical/infrared observations, or via CO. The sources we select in this pilot study are, SXDF 1100.001 (Orochi) (Ikarashi et al. 2011), SDP9, and SDP17 (Negrello et al. 2010; Lupu et al. 2010), SDSS J160705+533558 (Clements et al. 2009), and COSMOS-AzTEC1 (Smolcic et al. 2011). These sources have apparent infrared luminosities of $\gtrsim 10^{13} L_{\odot}$, and are promising sources for CO detection. We adopt $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.27$, $\Omega_{\Lambda} = 0.73$ for all of the analysis throughout this paper.

2. Instrumental Setup and Observations

The radio signal collected by the 45m telescope dish is received by the new two-beam, two-polarization, sideband separating receiver (TZ receiver) (Nakajima et al. 2012). The two beams are separated by $\sim 45''$ in the sky. The sky signal is separated into two linear polarizations by a waveguide-type ortho-mode transducer, and an IF quadrature hybrid is then used to separate the two sidebands. The local oscillator frequency tuning range is 80 – 115 GHz, with an IF bandwidth of 4 – 8 GHz. A future expansion to 4 – 12 GHz is planned.

The IF signal is amplified and down-converted to 2 – 4 GHz where the signal is digitized to 3-bits at the ADC. The digital signal is then transferred through optical fiber cables to the digital back-end. The digital back-end is an exact copy of the Atacama Compact Array (ACA) (Iguchi et al. 2009) FX-type correlator (Kamazaki et al. 2011). The 32 GHz total bandwidth is divided into 16 arrays, each with 2 GHz of bandwidth. When used at its maximum capability, it will accommodate the full 4 – 8 GHz IF signal from the TZ receiver.

Observations were carried out during the 2011/2012 winter observing season. The single sideband system temperature varied from 170 – 250 K¹, and we have tuned the orthogonal polarizations of each beam to the same sky frequency to gain $\sim \sqrt{2}$ in sensitivity. The sideband rejection ratio is typically $> 8\text{dB}$ at the center of the IF.

Since the source is always observed in one of the beams (16 to 19'' at the observed frequencies) of the TZ receiver, the dominant observing overhead is the telescope slewing time during switching, and it is ~ 7 seconds per cycle. We have adopted a 5 – 10 second switching cycle to optimize the observing overhead and the bandpass stability. The chopper-wheel method was used for absolute temperature calibration with an accuracy of 20%. The output auto-correlation spectrum, which contains 4096 channels with a frequency resolution of 488 kHz, is then calibrated on-line and stored in the database.

Data reduction was carried out using the facility data reduction software package Newstar. Since the 45m pointing accuracy is significantly affected by wind, only the data taken with wind velocity less than 5 m s^{-1} were used. The pointing accuracy under these conditions is typically 2–3'' in RMS. In addition, we flagged scans with visually poor baselines by inspecting each spectrum by eye. The final spectra are generated by integrating all of the good scans in the data, and a zeroth order baseline is subtracted from each spectrum. The average on-source time ranged from 5 – 11 hours. The antenna temperature is then converted to main-beam temperature by adopting a main-beam efficiency of 0.4, which is the average value obtained using the T100 receiver near the observing frequencies.² A typical 1σ sensitivity after one hour integration is $\sim 5\text{--}8 \text{ mJy}$ under these observing conditions and instrumental setup.

3. CO Spectra and Derived Quantities

The CO spectra are shown in Figure 1 and the derived properties are summarized in Table 1.

3.1. SDP17b & SDP9

SDP 17b was originally discovered in the Herschel-Astrophysical Terahertz Large Area Survey (H-ATLAS) (Eales et al. 2010) in the Science Demonstration Phase (SDP) as a population of submillimeter-bright strongly lensed galaxies (Negrello et al. 2010). This source was subsequently followed up with Z-Spec on board the Caltech Submillimeter Observatory, detecting CO (8–7), CO (7–6), CO (6–5) emission in the 200 – 300 GHz band (Lupu et al. 2010). The derived redshift is $z = 2.308$. In addition, Omont et al. (2011) have used the Plateau de Bure Interferometer (PdBI) to detect significant H_2O emission.

The CO (3–2) emission from SDP17b is the brightest among all lines detected in this pilot study. The 45m telescope observes a lower rotational transition of CO than those detected using Z-spec, allowing us to investigate the CO excitation conditions. While the uncertainties in the high-J CO line fluxes are relatively high, the CO excitation (Figure 1) appears low and may peak near the mid-J lines detected at Z-Spec. This evidence for relatively low CO excitation is consistent with other SMGs studied in multi-line CO (Weiss et al. 2007).

¹ The receiver temperature is expected to improve significantly next year with the installation of new components.

² See status report; http://www.nro.nao.ac.jp/~nro45mrt/prop/status/Status_R11.html

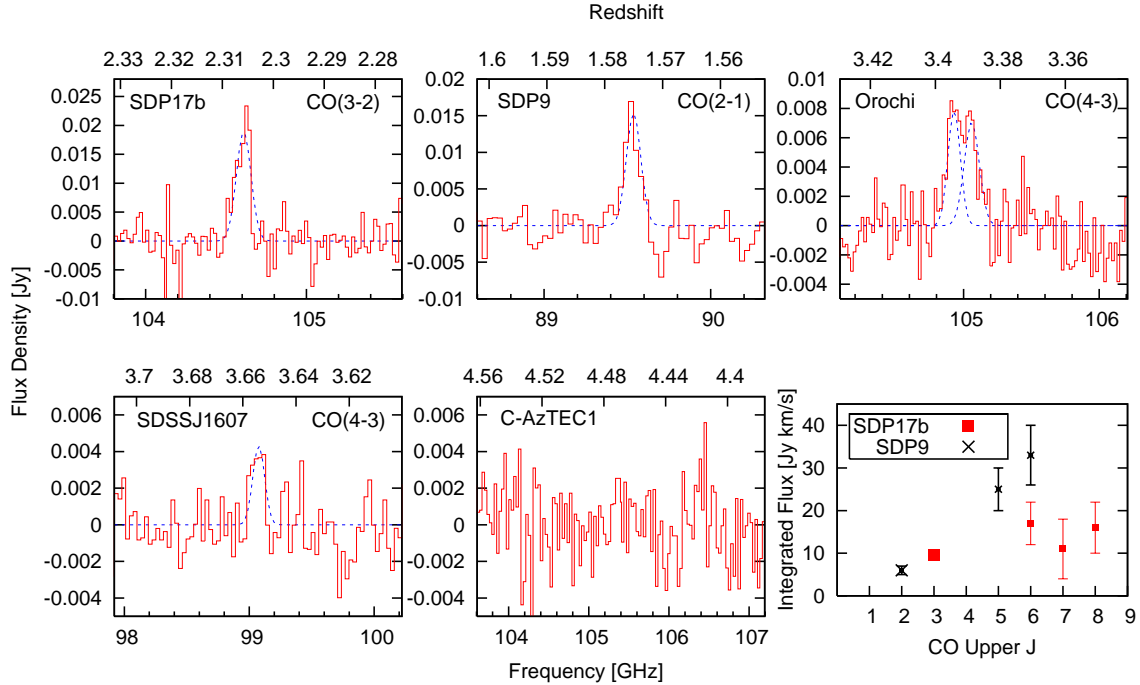


Fig. 1. The CO spectra are binned with 30 MHz spectral resolution for SDP9, SDSS J1607 and C-AzTEC1, and 20 MHz for SDP17b and Orochi. Gaussian fits to the detected spectra are shown in dashed blue lines. The lower right panel shows the relationship between integrated intensity [in Jy km s⁻¹] and the CO Upper J transition for the two SDP sources. The CO (6–5), CO (7–6), CO (8–7) for SDP17b and CO (6–5), CO (5–4) for SDP9 are taken from Lupu et al. (2010)

SDP9 is another source detected in the H-ATLAS. The CO (6–5) and CO (5–4) emission have been detected with Z-Spec (Lupu et al. 2010), yielding a redshift of $z = 1.578$. We detected the CO (2–1) line from SDP9 with 8-sigma confidence. The derived redshift is 0.003 smaller than the Z-Spec redshift. In contrast to SDP17b, the CO excitation appears high and does not show significant signs of decrement at mid-J CO lines. Detections of higher-J CO lines are necessary to understand the excitation conditions of this SMG better.

3.2. SXDF1100.001 (Orochi/HXMM02)

SXDF1100.001 (Orochi) is a $L_{\text{IR}} \sim 10^{13} L_{\odot}$ SMG discovered using the AzTEC camera (Wilson et al. 2008) on the Atacama Submillimeter Telescope Experiment (ASTE) (Ezawa et al. 2004; Ezawa et al. 2008). Its 1.1 mm flux density is 37 mJy, making this the brightest SMG found in the Subaru/XMM-Newton Deep Field (SXDF) and may be gravitationally lensed by a foreground galaxy (Ikarashi et al. 2011). This source is detected by Herschel Multi-tiered Extragalactic Survey (HerMES), also known as HXMM02, and found to be very bright in Herschel/SPIRE bands (Wardlow et al. 2012). The photometric redshift was estimated to be $z = 3.4^{+0.7}_{-0.5}$ using submm to radio continuum fluxes from SMA, Z-Spec, CARMA, and VLA (Ikarashi et al. 2011). Subsequent CO (3–2), (4–3), and (5–4) detections with CARMA and PdBI confirm that

HXMM02 is at $z = 3.395$ (Wardlow et al. 2012). The CO (1–0) is also measured using GBT (Inoue et al. 2012, in prep.).

The CO (4–3) line of Orochi is best fit with a two component Gaussian. The double peak spectrum may suggest a merging galaxy, or a presence of systematic rotation of a large gas concentration. Such double peak profiles are often seen in past detections toward SMGs (Greve et al. 2005) and in BzK selected galaxies (Daddi et al. 2010).

3.3. SDSS J160705+533558

SDSS J160705+533558 (SDSS J1607) is a submm bright quasar at $z = 3.653$ with an infrared luminosity exceeding $10^{14} L_{\odot}$ (Clements et al. 2009). Followup 1'' SMA observation has found a resolved dust component with the peak located $\sim 2''$ north of the optical quasar. The large submm flux is equivalent to a dusty SFR of 3000 – 8000 $M_{\odot} \text{ yr}^{-1}$. The submm emission appears to be resolved in the north-south direction, and Clements et al. (2009) suggest either a merging galaxy or an interaction with an AGN jet for the unusual submm morphology.

We tentatively detect the CO (4–3) line in SDSS J1607. The linewidth and molecular gas mass are both consistent with other high redshift quasars detected in CO (Wang et al. 2010), but the gas depletion time scale ($M_{\text{H}_2}/\text{SFR}$) of 14 – 37 Myr is slightly smaller than the average of quasars (Riechers 2011). This suggests a short and vigorous burst

Table 1. Observational Properties and Derived Parameters

Source	Transition	RMS [mJy] ¹	z	FWHM [km s ⁻¹]	S_{CO}	Δv [Jy km s ⁻¹]	M_{H_2} [M _⊙] ²
SDP17b	CO (3-2)	4.7	2.306 ± 0.001	440 ± 30		9.6 ± 1.9	$(4.3 \pm 0.9) \times 10^{11}$
SDP9	CO (2-1)	2.2	1.575 ± 0.001	480 ± 30		6.1 ± 1.2	$(1.9 \pm 0.4) \times 10^{11}$
Orochi ³	CO (4-3)	1.9	3.394 ± 0.003	430 ± 40		5.8 ± 1.2	$(3.4 \pm 0.7) \times 10^{11}$
			3.388 ± 0.004	530 ± 40			
SDSSJ1607	CO (4-3)	1.7	3.653 ± 0.001	480 ± 70		1.5 ± 0.4	$(1.1 \pm 0.2) \times 10^{11}$
C-AzTEC1	—	2.0	—	—		< 2.4	$< 1.9 \times 10^{11}$

¹ The root mean squared of the line free region of the spectrum using the channel binning shown in Figure 1.

² Using CO line ratios in Bothwell et al. (2012) and the CO-to-H₂ conversion factor of 0.8 [M_⊙ (K km s⁻¹ pc²)⁻¹].

³ The redshift and FWHM of Orochi are derived using a two Gaussian fit, but the integrated intensity and mass are for the entire spectrum.

of star formation in SDSS J1607.

3.4. COSMOS-AzTEC1

COSMOS-AzTEC1 is a source discovered by the AzTEC survey on JCMT (Scott et al. 2008), followed up by the Submillimeter Array (Younger et al. 2007). Subsequent Keck DEIMOS spectroscopy has derived a redshift of $z \approx 4.64$ but the CO (5-4) emission was not detected in the redshift range 4.56 – 4.76 and 4.94 – 5.02 (Smolcic et al. 2011). We searched for the CO emission in the redshift range 4.38 – 4.56, but did not detect any significant emission with a 3-sigma mass upper limit of 1.9×10^{11} M_⊙, assuming a line width of 400 km s⁻¹ and CO (5-4) to CO (1-0) ratio of 0.32 (Bothwell et al. 2012). As discussed in Smolcic et al. (2011), these non-detections could imply a low CO excitation or an incorrect redshift.

4. Summary and Future Prospects

We present new CO observations toward five submm bright high redshift sources from the upgraded Nobeyama 45m telescope. All of the detected sources have large molecular gas mass ($M_{H_2} \sim 10^{11}$ M_⊙) and line-widths (430 – 530 km s⁻¹). One source (Orochi) shows a double peak spectrum. We plan to expand this project by tuning the two different polarizations to different frequencies, allowing us to instantaneously observe 16 GHz bandwidth in a single beam. Further, a new dual-color TES bolometer camera (Oshima et al., in prep) mounted on ASTE will detect and provide constraints to the redshifts of the SMGs. The bright ($S_{850} \gtrsim 10$ mJy) sources will be excellent targets for CO followup at the 45m.

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